DIELECTRIC STUDIES IN THE DEVELOPMENT OF HIGH ENERGY DENSITY PULSED POWER CAPACITORS*

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Abstract

In an effort to increase the energy density of high voltage capacitors to greater than 5 J/cm^3 for compact pulsed power sources, high dielectric constant materials with high dielectric strength are under continued development at the University of Missouri. The materials are modified versions of composites recently developed for compact dielectric-loaded antennas. While the composites developed for antenna systems were developed specifically for use at 100s of MHz to several GHz, the requirements of capacitor applications present unique challenges. In particular, the leakage current must be minimized to efficiently store the energy for long periods of time, and the dielectric losses must be considered at the relatively lower frequencies up to several 10s of MHz. This paper details the dielectric properties of the materials under development for high energy density pulsed power capacitors. The dielectric constant and loss are reported at frequencies relevant for capacitor applications. The leakage current under high voltage conditions is evaluated, and waveforms from the fast discharge of sample capacitors are analyzed. Finally, projections are provided on how the materials may be scaled from small capacitors for dielectric evaluation to full-size prototypes.

I. INTRODUCTION

Increasing the energy density of capacitors can be accomplished by operating at higher electric field levels, incorporating dielectric materials with higher dielectric constants, and improving the capacitor packaging. Due to the dependence on the square of the operating electric field, the use of materials with a high dielectric strength is required for high energy density high voltage capacitors. An approach in many leading commercially available and of emerging high energy density capacitors is the use metalized electrode polymer films [1]. The relatively high breakdown strength of the polymer films at 500 – 800 MV/m enables high energy density to be achieved, and the self-healing capability of the metalized electrodes increases the capacitor lifetime [1].

A second approach to achieving high energy density pulsed power capacitors is based on the use of high dielectric constant composite materials. In this approach, the operating electric field within the dielectric material is typically less than that used in polymer films, but the high energy density is maintained or increased further due to the much higher dielectric constant. While polymer-ceramic composites have been developed for many years for low voltage applications, there has been an increase in composite research directed at pulsed power capacitors [2, 3].

Advances have recently been made in high dielectric constant composite materials at the University of Missouri through the development of materials intended for high power antenna applications. Three classes of materials have been developed for high power antennas with room temperature dielectric constants measured at 200 MHz of 45, 100, and 550 [4]. These materials were also developed to have a high dielectric strength for operation in antennas driven at high peak power, but the high dielectric constant of the materials allows high energy density to be achieved at field levels below 100 MV/m. Due to the encouraging results of the material development for high power antennas and the flexibility available in modifying the components of the composite, a preliminary study was conducted to investigate the transition of the high dielectric constant composite materials to high energy density capacitor applications. This report includes measurements of material testing on three materials, two of which were newly developed for this study, under both low voltage and high voltage conditions. Preliminary capacitor designs are also presented for two high voltage capacitors under development.

II. MEASUREMENT METHODS

The high dielectric constant composite materials under consideration were made into samples with a 25.4 mm diameter and a thickness between 2 and 2.5 mm. Small capacitors were prepared with the high dielectric constant composites by sputtering platinum electrodes with a diameter of approximately 12 mm directly onto the surfaces of the composite. To protect the sputtered electrode from abrasion when making contact with other electrodes, the sputtered area was coated with a conductive silver-filled paste. Each sample was mounted in a transparent acrylic holder for handling and electrical connection. The thickness of each sample was determined prior to testing.

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14. ABSTRACT
In an effort to increase the energy density of high voltage capacitors to greater than 5 J/cm3 for compact pulsed power sources, high dielectric constant materials with high dielectric strength are under continued development at the University of Missouri. The materials are modified versions of composites recently developed for compact dielectric-loaded antennas. While the composites developed for antenna systems were developed specifically for use at 100s of MHz to several GHz, the requirements of capacitor applications present unique challenges. In particular, the leakage current must be minimized to efficiently store the energy for long periods of time, and the dielectric losses must be considered at the relatively lower frequencies up to several 10s of MHz. This paper details the dielectric properties of the materials under development for high energy density pulsed power capacitors. The dielectric constant and loss are reported at frequencies relevant for capacitor applications. The leakage current under high voltage conditions is evaluated, and waveforms from the fast discharge of sample capacitors are analyzed. Finally, projections are provided on how the materials may be scaled from small capacitors for dielectric evaluation to full-size prototypes.

15. SUBJECT TERMS
Non-lethal weapons; capacitor; dielectric; composite materials

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The effective dielectric constants of the composite materials were calculated from the capacitance values and the geometry of the parallel-plate capacitor. The effect of the fringe fields was ignored as is common in practice as the additional capacitance obtained from fringe fields when measuring a high dielectric constant material are relatively small. All measurements were conducted at room temperature.

A. Low Voltage Permittivity Measurements

The Agilent 4285A Precision LCR Meter was used for measurements of capacitance, C_p, and dissipation factor, D, between 75 kHz and 30 MHz. A list of frequencies of interest was entered on the LCR meter for automated measurement at 100 kHz, 200 kHz, 500 kHz, 1 MHz, 2 MHz, 5 MHz, 10 MHz, 15 MHz, and 20 MHz. High frequency measurements of the dissipation factor are limited by the accuracy of the instrument to below 10 MHz.

B. High Voltage Capacitive Discharge

A simple high voltage capacitive discharge test stand was used to demonstrate the ability of the sample capacitors to be charged to high voltage and discharged into a resistive load. Post-processing of the data enabled the dielectric constant of the material to be estimated while under high voltage conditions.

A high voltage IGBT stack was used to switch the capacitor under test into a known load resistance. The charging voltage is monitored with a Fluke 80K-40 1000:1 voltage probe. The fast discharge of the capacitor is monitored with a Northstar PVM6 1000:1 high voltage probe. The discharge is recorded on a Tektronix TDS 5054B oscilloscope. A custom Matlab program automates the analysis of the data by producing a curve fit to the measured RC decay and calculating values of capacitance and effective dielectric constant given the known load resistance and sample geometry. Non-inductive resistors were used for the load resistor with values ranging from 1 Ω to 105 kΩ.

From the voltage versus. time plots obtained from each capacitive discharge, it is possible to determine the capacitance of the capacitor under test if the voltage is a known constant. Two points along the discharge curve, represented as times $t_1$and t_2 at which the voltage is V_1 and V_2, respectively, are needed to calculate the capacitance. With the data from those two points, the capacitance is calculated using equation (1). The capacitance of the test sample is represented at C [F], and the known resistance in series with the capacitor is represented as R_L [Ω]. The effective dielectric constant, ε_r, is then calculated using the capacitance and the dimensions of the capacitor.

$$C = \frac{t_2 - t_1}{R_L ln\left(\frac{V_1}{V_2}\right)} \tag{1}$$

A commercial doorknob high voltage capacitor was used to test the high voltage capacitive discharge test stand and verify its measurements before testing the capacitors made with the composite materials. When charged to -1 kV and discharged into a 10.4 kΩ load in two separate tests, the capacitance of the doorknob capacitor was calculated from the discharge curve to be 5.52 nF and 5.61 nF. These calculated values are within 5% of the value measured with a Sencore LC103 of 5.4 nF.

C. Sencore LC103

The Sencore LC103 Inductor and Capacitor Analyzer was primarily used to test the leakage current of the sample capacitors with an applied voltage of up to 1 kV. The LC103 is rated to measure currents as low as 0.01 µA [5]. When the leakage current is too low to be accurately measured, the LC103 outputs a leakage resistance of greater than 1 GΩ. The capacitance was also measured. The capacitance measurement feature of the LC103 operates at low voltage. Due to the measurement method in which the charging waveform is analyzed, a specific frequency cannot be assigned to the measurement. However, the frequency content of the measurement signal is believed to be below the range of frequencies measured with the 4285A LCR meter.

III. MU-AGAX

The composite material with the highest dielectric constant developed for dielectric-loading of antennas, MU550, had a dielectric constant up to approximately 550 at 200 MHz [4]. However, under DC charging conditions, one of the components of the MU550 composite enables charge transfer that results in a non-negligible leakage current. Therefore, MU550 was determined to not be a good candidate for capacitor applications. Material substitutions were made in the composition of MU550 to replace the components responsible for the leakage current. While these modifications lower the dielectric constant of this type of composite, several new composites were produced with improved losses and leakage current. One of these modified composites is reported here at MU-AGAX.

Table 1 lists the effective dielectric constant and dissipation factor taken at low voltage with the LCR meters for MU-AGAX. MU-AGAX exhibits a lower degree of dispersion but also a lower dielectric constant than the other two candidate materials. The dielectric constant is between approximately 135 and 150 at the frequencies of greatest interest. The losses are low throughout the frequency range, remaining below 0.027.

Table 1. MUAGAX LCR Measurements

Frequency (kHz)	Dissipation Factor	Effective Dielectric Constant
100	0.019	148.50
200	0.020	147.17
500	0.022	145.37
1000	0.022	143.91
2000	0.024	142.03
5000	0.027	136.93

Table 2 displays the measurement results of high voltage capacitive discharge measurements for MU-AGAX. It was observed that the effective dielectric constant is much higher when measured during a high voltage discharge. The effective dielectric constant of MU-AGAX when discharged from -1 kV was approximately 250. Due to consistency of this increase in the effective dielectric constant under high electric field conditions, the effect is believed to be real, but artificial effects due to electrode contact and other potential causes will continue to be investigated.

Table 2. Summary of MU-AGAX high voltage capacitive discharge measurements

Voltage (kV)	Effective ε_r
1	253.59
1	249.81
2	243.04
3	284.41
4	267.48
5	259.67

Table 3 displays the values obtained for MUAGAX with the Sencore LC103. The effective dielectric constant of 159.53 agrees with the low voltage measurements obtained with the LCR meter. The value is believed to be slightly higher than the values reported in Table 1 due to the lower frequency content of the measurement signal of the LC103. Since the leakage current was very low with an applied voltage of 1 kV, the exact leakage resistance cannot be determined. However, the leakage resistance is verified to be greater than 1 GΩ.

Table 3. MU-AGAX measurements on the Sencore LC103

Material	Effective ε_r	Leakage Resistance at 1 kV (GΩ)
MU-AGAX	159.53	Greater than 1

IV. MU100

MU100 is the only candidate material developed for antenna applications that was directly applied without modification to the capacitor application. MU100 is an excellent candidate for capacitor applications due to its high dielectric constant, low leakage current, high dielectric strength, and the lowered risk associated with a material that has been used in other high power prototypes. Table 4 displays the low voltage dielectric constant and loss measurements taken on a sample capacitor of MU100. At low voltage, the dielectric constant in this frequency range is around 200. The difference between the value of 200 obtained in these measurements and the previously reported value of 100 for MU100 is explained by two reasons. First, the method used for measurements of the permittivity between 200 MHz and 4.5 GHz for antenna characterization uses a direct contact between the probe and material under test. Due to imperfections in the probe-material contact, the dielectric constant is underestimated from its actual value [4]. Second, due to the slow decrease in the dielectric constant of the material with increasing frequency, the value is different at the frequencies applicable to antenna and capacitor applications.

Table 4. MU100 LCR Measurements

Frequency (kHz)	Dissipation Factor	Effective ε_r
100	0.013	209.90
200	0.013	208.79
500	0.015	207.13
1000	0.017	205.81
2000	0.020	203.96
5000	0.030	198.07

Table 5 lists the capacitance and effective dielectric constant of the MU100 sample obtained from high voltage capacitive discharge measurements. The effective dielectric constant when discharged from voltages ranging from -1 kV to -5 kV was consistently observed to be between approximately 310 and 320. As in the case of MU-AGAX, the effective dielectric constant values were measured higher when the material is biased with a high electric field.

Table 5. High voltage capacitive discharge measurements of MU100

Voltage (kV)	Effective ε_r
1	321.07
2	310.40
3	318.18
4	318.76
5	320.18

Table 6 shows the results of measurements of MU100 with the Sencore LC Analyzer. The effective dielectric constant was calculated to be approximately 224.4, which agrees well with the LCR measurements and with the understanding that the frequency of the Sencore measurement is below the frequencies displayed in Table 4. The leakage current obtained from a test voltage of 1 kV was too small to calculate an exact leakage resistance, but the leakage resistance was verified to be greater than 1 GΩ.

Table 6. MU100 Measurements from the Sencore LC Analyzer

Material	Effective ε_r	Leakage Resistance at 1 kV (GΩ)
MU100	224.40	Greater than 1

V. MU-PBC2

By modifying the ceramic content of MU100 while maintaining the same binder and manufacturing process, a new composite called MU-PBC2 was developed. The low voltage LCR measurements of MU-PBC2 are given in Table 7. At the frequencies listed between 100 kHz and 5 MHz, the dielectric constant ranges between approximately 340 and 370. The losses remain low throughout this range of interest with a maximum loss observed at 5 MHz of 0.027.

Table 7. MU-PBC2 Low Voltage Measurements

Frequency (kHz)	Dissipation Factor	Effective ε_r
100	0.014	368.30
200	0.014	366.24
500	0.015	363.49
1000	0.017	360.87
2000	0.021	356.64
5000	0.027	341.12

The high voltage capacitive discharge data for MUPBC2 is summarized in Table 8. As observed in MU-AGAX and MU100, the effective dielectric constant measured under a high electric field was consistently much higher than that observed from low voltage LCR meter measurements. The effective dielectric constant of discharges from -2 kV and -3 kV were also higher than that seen for discharges from -1 kV. A common value observed in discharges from -2 kV and -3 kV was approximately 568.

Table 8. Summary of MU-PBC2 high voltage capacitive discharge measurements

Voltage (kV)	Effective ε_r
1	527.63
1	481.31
2	567.86
2	572.78
2	567.86
3	583.98
3	568.16
3	567.86

Table 9 displays the results of measurements of MU-PBC2 obtained with the Sencore LC Analyzer. The effective dielectric constant of approximately 394 agrees with low frequency measurements obtained with the LCR meter. At an applied voltage of 1 kV, the leakage resistance was measured to be 1.3 GΩ.

Table 9. MU-PBC2 measurements on the Sencore LC Analyzer

Material	Effective ε_r	Leakage Resistance at 1 kV (GΩ)
MU-PBC2	394.41	1.3

VI. PRELIMINARY HIGH VOLTAGE CAPACITOR DESIGNS

Of the many composites developed and tested as a part of this study, MU100 and MU-PBC2 were considered the best candidate materials available at this time. Preliminary designs were prepared for two high voltage capacitors using both of these materials.

A. Design 1: 55 kV, 40 nF, > 1.2 J/cm^3

The specifications for the first capacitor design are for a 40 nF capacitor operating at 55 kV and a packaged energy density of greater than 1.2 J/cm^3. As shown in Table 10, the electrode separation distance using MU-PBC2 with a dielectric constant of 568 has been designed to be 1.575 mm for operation at 34.92 MV/m. Operation at this relatively low field level could improve the capacitor lifetime when operated under large reverse voltage. It was considered an advantage in context of lifetime issues for high energy density operation to form the capacitor in a single capacitive layer. Using an electrode radius of 6.25 cm, 40 nF can be achieved with only 1 layer given the high dielectric constant of MU-PBC2. Packaging of the capacitor was estimated to increase the capacitor volume by 50%. The estimated packaged energy density of 2.04 J/cm^3 exceeds the desired specifications of 1.2 J/cm^3.

Table 10. Capacitor Parameters for Design 1 Using MU-PBC2

Application	Voltage (kV)	*C* (nF)	Energy Stored (J)
2	55	40	60.5
Dielectric Material	**Dielectric Constant**	**Electrode Separation (mm)**	**Average Field (MV/m)**
MUPBC2	568	1.575	34.92
Electrode Radius (cm)	**Electrode Area (cm^2)**	**Single Layer *C* (nF)**	**No. of Layers**
6.35	126.68	40.44	1.0
Material Volume (cm^3)	**Material Energy Density (J/cm^3)**	**Packaged Volume (cm^3)**	**Packaged Energy Density (J/cm^3)**
19.74	3.07	29.60	2.04

Adapting the design for MU100, the value used for the dielectric constant was reduced to 300. With this lower value, the capacitor must operate at a higher electric field to achieve the desired capacitance in a single layer with a radius of 6.35 cm. The layer thickness was designed to be 0.825 mm, corresponding to an average electric field of 66.67 MV/m. Again assuming the packaging increases the capacitor volume by 50%, the packaged energy density is 3.93 J/cm^3, which is more than twice the requirement.

Table 11. Capacitor Parameters for Design 1 Using MU100

Application	Operating Voltage (kV)	*C* (nF)	Energy Stored (J)
2	55	40	60.5
Dielectric Material	**Dielectric Constant**	**Electrode Separation (mm)**	**Average Field (MV/m)**
MU100	300	0.825	66.67
Electrode Radius (cm)	**Electrode Area (cm^2)**	**Single Layer *C* (nF)**	**No. of Layers**
6.35	126.68	40.78	1.0
Material Volume (cm^3)	**Material Energy Density (J/cm^3)**	**Packaged Volume (cm^3)**	**Packaged Energy Density (J/cm^3)**
10.25	5.90	15.38	3.93

B. Design 2: 30 kV, 5 nF, 5 J/cm^3

A second capacitor design was calculated for a 30 kV capacitor of 5 nF with a packaged energy density of 5 J/cm^3. Table 12 displays the parameters for a capacitor meeting these specifications designed with the MU-PBC2 material. The small capacitance of 5 nF and relatively low operating voltage of 30 kV result in a lower total energy stored at 2.25 J. However, the specifications require a higher energy density than that specified in design 1. The designed electrode spacing of 0.55 mm results in an average electric field in the composite of 54.54 MV/m. The capacitor is designed as a single layer capacitor with an electrode radius of just 1.35 cm. Assuming a 50% increase in volume due to the packaging, this compact capacitor would have a packaged energy density of approximately 5.1 J/cm^3, meeting the desired specification.

Table 12. Capacitor Projections Using MU-PBC2

Design	Voltage (kV)	*C* (nF)	Energy Stored (J)
2	30	5	2.25
Dielectric Material	**Dielectric Constant**	**Electrode Separation (mm)**	**Average Field (MV/m)**
MU-PBC2	568	0.55	54.54
Electrode Radius (cm)	**Electrode Area (cm^2)**	**Single Layer *C* (nF)**	**No. of Layers**
1.35	5.73	5.23	1.0
Material Volume (cm^3)	**Material Energy Density (J/cm^3)**	**Packaged Volume (cm^3)**	**Packaged Energy Density (J/cm^3)**
0.30	7.48	0.44	5.1

Table 13 presents a design using the MU100 material with a dielectric constant of 300. Due to the lower dielectric constant, the electrode separation was decreased to 0.4 mm, and the electrode radius was increased to 1.55 cm. The operating electric field is increased to 75 MV/m. These geometrical changes allow the packaged energy density to again be slightly greater than 5 J/cm^3.

Table 13. Capacitor Parameters Using MU100

Application	Voltage (kV)	*C* (nF)	Energy Stored (J)
3.1	30	5	2.25
Dielectric Material	**Dielectric Constant**	**Thickness (mm)**	**Average Field (MV/m)**
MU100	300	0.4	75
Electrode Radius (cm)	**Electrode Area (cm^2)**	**Single Layer *C* (nF)**	**No. of Layers**
1.55	7.55	5.01	1.0
Material Volume (cm^3)	**Material Energy Density (J/cm^3)**	**Packaged Volume (cm^3)**	**Packaged Energy Density (J/cm^3)**
0.30	7.47	0.44	5.1

VII. CONCLUSIONS

Materials developed specifically for high power devices at the Center for Physical and Power Electronics at the University of Missouri were investigated for transition to high voltage, high energy density capacitor applications. A six-month study has and test program demonstrated several important technological and design criteria to provide a path forward towards full prototype development. First, it has been demonstrated that the materials can effectively act as capacitor dielectrics. Measurements have shown that the materials have a high dielectric constant when charged and discharged under high voltage conditions. Two candidate materials, MU100 and MU-PBC2, were measured to have effective dielectric constants of approximately 320 and 568, respectively, when discharged from high voltage. Such high dielectric constants, when combined with high operating field levels between 10 and 100 MV/m, enable high energy densities between 1 and 10 J/cm^3 to be achieved with the potential to reach even higher energy densities under higher peak field conditions. Second, measurements have demonstrated a high resistance to leakage current when charged under DC conditions. At 1 kV applied voltage, the materials detailed in this report had a leakage resistance of greater than 1 GΩ. MU100 and MU-AGAX are believed to have leakage resistances significantly higher than 1 GΩ. Such high leakage resistances enable the capacitors to efficiently charge and store energy capacitively. Third, the losses of small-scale capacitors have been measured at low voltage. The losses at the relevant capacitor frequencies from 100 Hz to greater than 1 MHz have been shown to consistently be below about 3% in all three materials presented in this report. Fourth, designs have been prepared that meet or exceed the high energy density goals, allowing for packaged energy densities exceeding 5 J/cm^3 in one design. Designs for capacitances up to 40 nF can be achieved in a single layer capacitor. Based on this preliminary work, a viable path forward has been established to transition the high dielectric constant composites to high voltage capacitor applications, and additional work is planned for additional material development and testing, material dielectric strength and lifetime testing, and production of full-scale prototypes.

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